Czech Technical University
in Prague

Rigaku

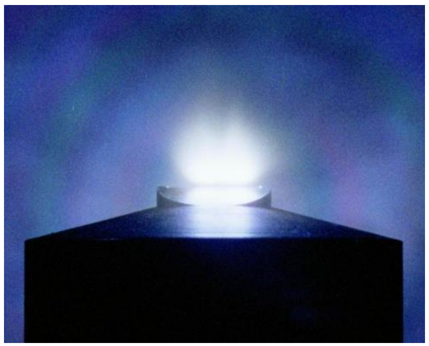
Ar plasma discharge sources for EUV/SXR metrology and imaging

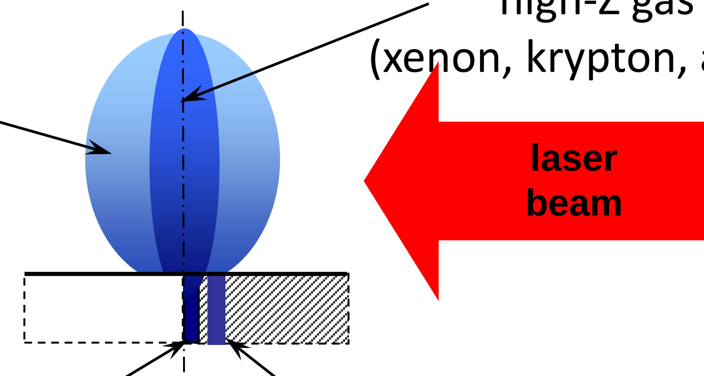
Ladislav Pina

Motivation

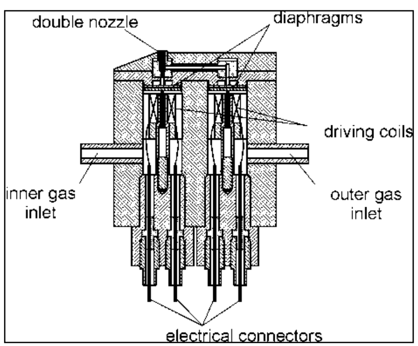
- V. Bakshi - Industry Requirements for Broad Band EUV Sources for Next-generation Wafer Inspection Applications (EUVS 2017)
- B. M. Barnes et al (NIST) - In this study, a 47 nm wavelength yielded enhancements in the signal-to-noise by a factor of five compared to longer wavelengths and in the differential intensities by as much as three orders-of-magnitude compared to 13 nm, the actinic wavelength for EUV semiconductor manufacturing.
- DPP lasing at λ=46.9 nm has been already demonstrated (S. Heinbuch, J. Rocca (Colorado Univ.), A. Ritucci (Aquilla Univ.), K. Kolacek (IPP CAS), A. Jancarek (CTU), …).
- EUV optics development (focusing, collimating and spectral filtering)
- SXR microscopy

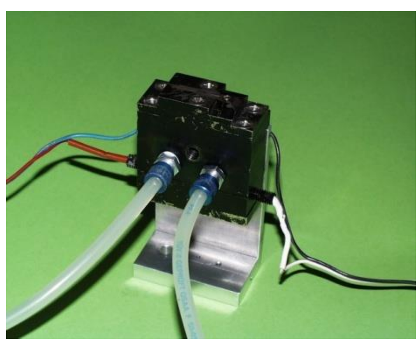
Laser Produced Plasma – gas puff target



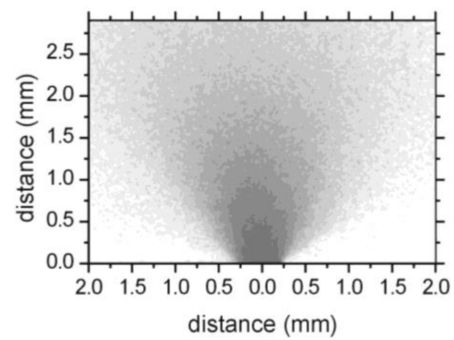


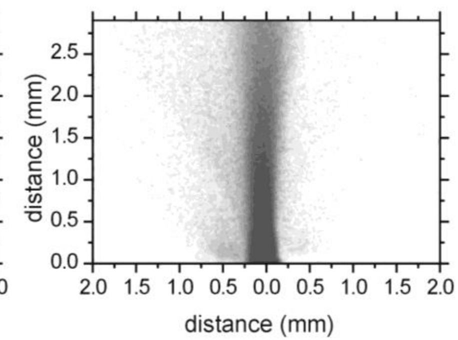
- **electromagnetic valve system**





- **X-ray backlighting images**

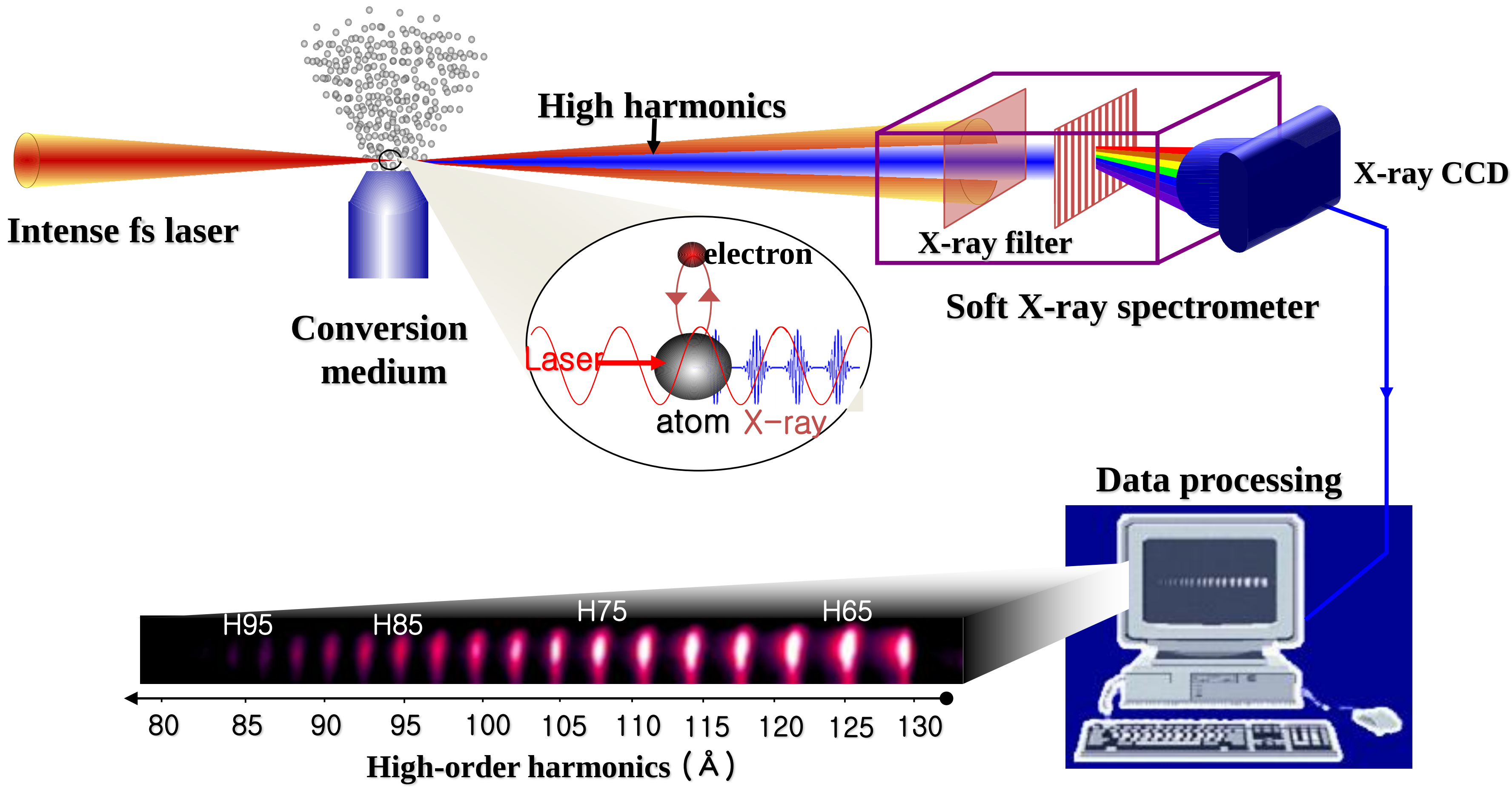




H. Fiedorowicz *et al. Appl.Phys. B 70 (2000) 305; Patent No.: US 6,469,310 B1*

HHG using femtosecond laser

Typical setup



KAIST

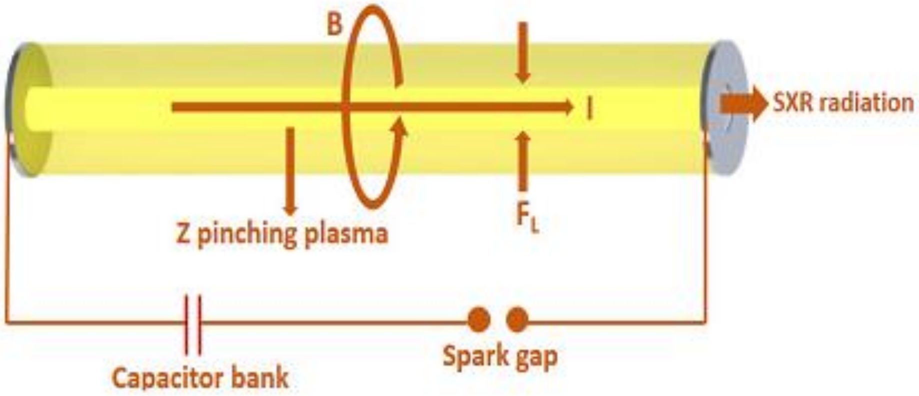
Prof. Chang Hee Nam
K. Jakubzcak

Coherent EUV HHG source driven by ultrashort laser pulses at FNSPE

Laser parameters:
- E = up to 12 mJ
- Δt = ~ 60 fs
- D < ~ 1”
- Rep. rate 10 Hz

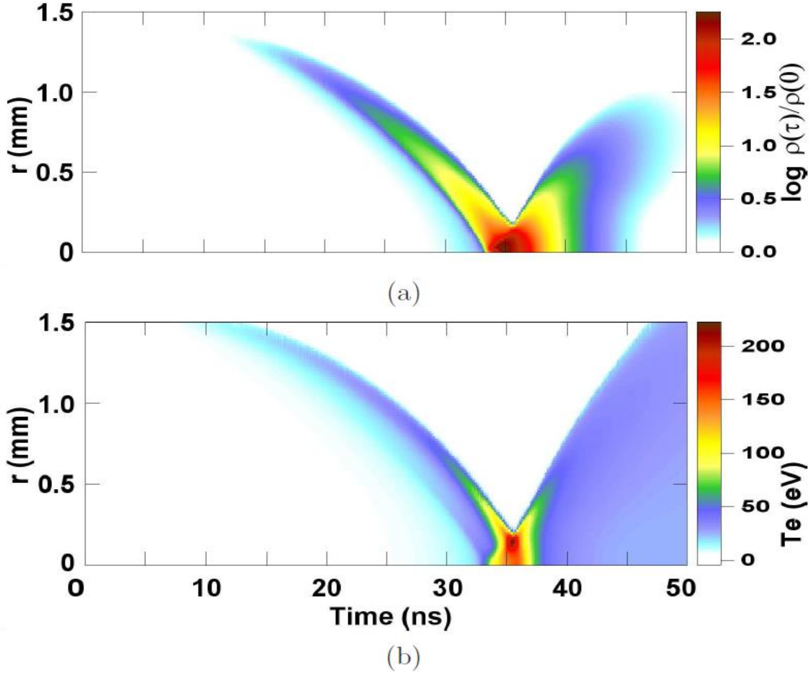
Faculty of Nuclear Sciences and Physical Engineering
Femtosecond Lab
CTU

Capillary discharge source



Introduction

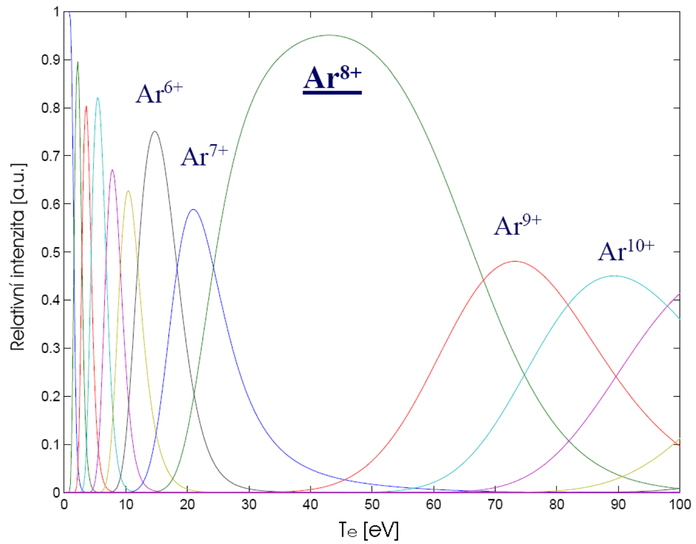
Z-pinching Capillary Discharge



- **Radial compression** of plasma by Lorenz **force**
- Plasma **heating**
- Fast **cooling** of plasma due adiabatic expansion
- **Preionisation** for discharge **stabilisation**

P. Vrba, M. Vrbová, N. A. Bobrova, and P. V. Sasorov, "Modelling of a nitrogen X-ray laser pumped by capillary discharge," *Cent. Eur. J. Phys.*, vol. 3, no. 4, pp. 564–580, 2005

Ar^{8+} LASER 46.9 nm CTU

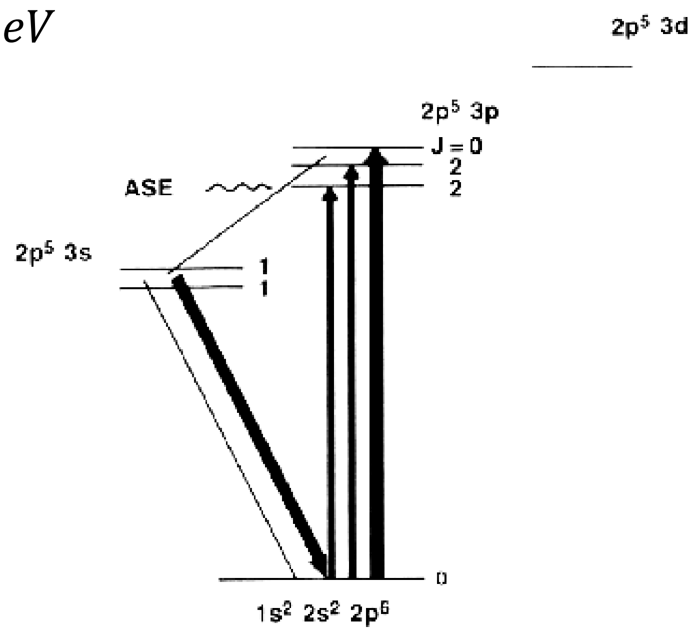


Argon ion abundance dependence on plasma electron temperature

Conditions for ASE

$$T_e = 40 \div 100\ eV$$
$$N_e \sim 10^{19} cm^{-3}$$

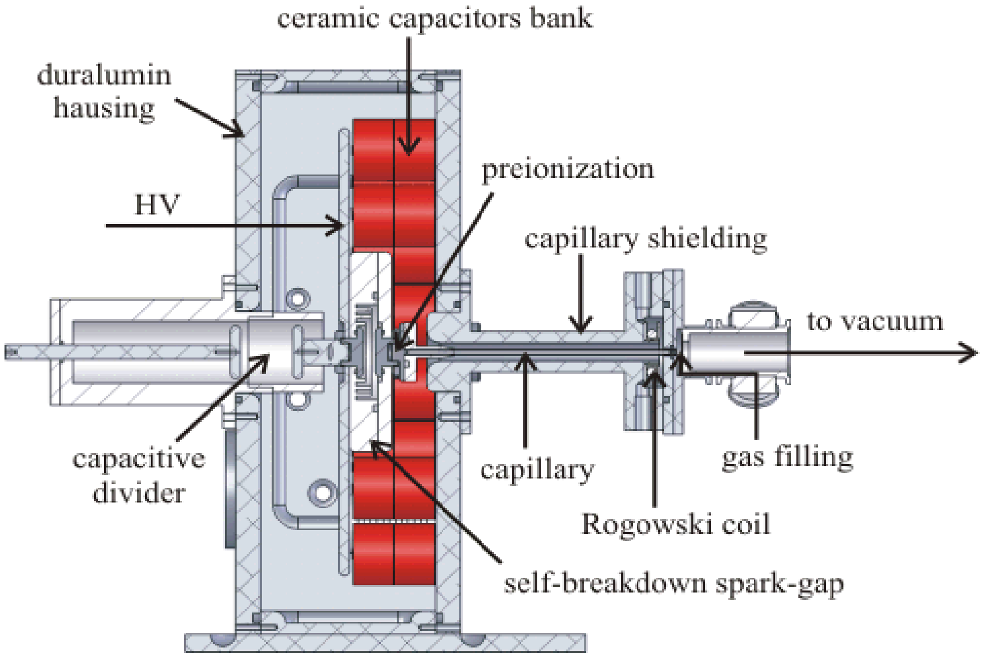
Z-pinching discharge with ***I* ≈ 20 kA**, current rise time ***t* ≈ 60 ns** and capillary length ***L* ≈ 200 mm** are necessary conditions for lasing



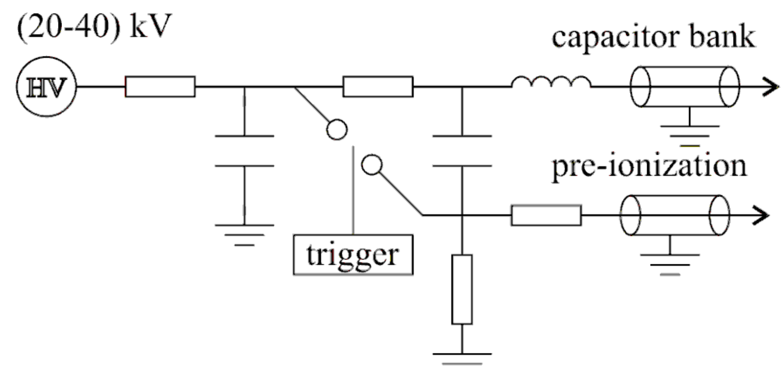
Important energy levels in neon-lke lasing plasma

Ar^{8+} LASER 46.9 nm CTU

CAPILLARY DISCHARGE APPARATUS FOR INTENSE EUV RADIATION GENERATION



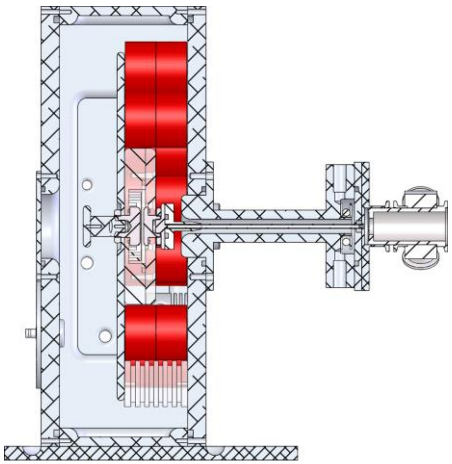
Main discharge unit



- **Ceramic Capacitors (1.25 ÷ 31 nF).**
- **Al_2O_3 capillary, 3.2mm dia., 20cm long.**
- **Low inductance -> high d*I*/d*t*.**
- **Pulse-charged: 1x Marx + coil.**
- **Rogowski coil.**

CTU Prague, Fac. of Nucl. Sci

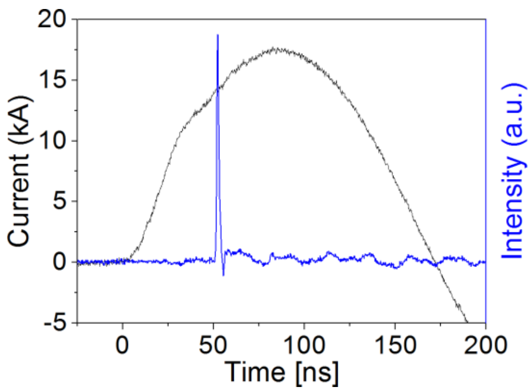
Ar^{8+} LASER 46.9 nm CTU



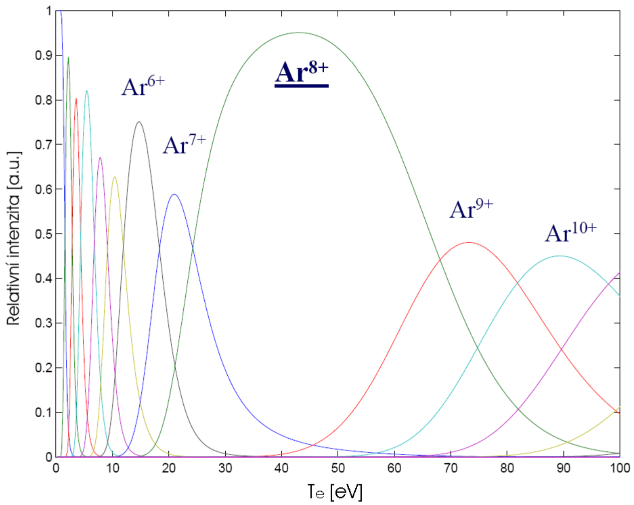
Basic driver parameters

Capillary (L x ID)	200 × 3.2 mm
Charging voltage	60 kV
Current maximum	18 kA
Rise-time (10-90%)	55 ns

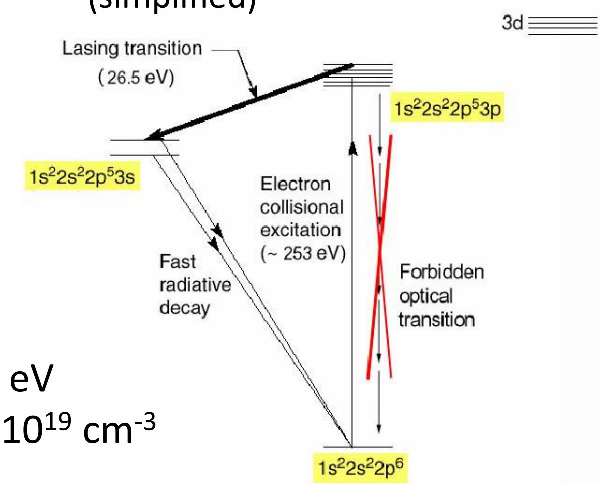
Capillary current and AXUV photo-diode signal, 0.8 um Al filtered



Argon ions abundance with resp. to T_e at N_e = 1e18 cm^{-3}



Energy levels of Ne-like Argon (simplified)



$T_e = 60 \div 90$ eV

$N_e \sim 10^{18} \div 10^{19}$ cm^{-3}

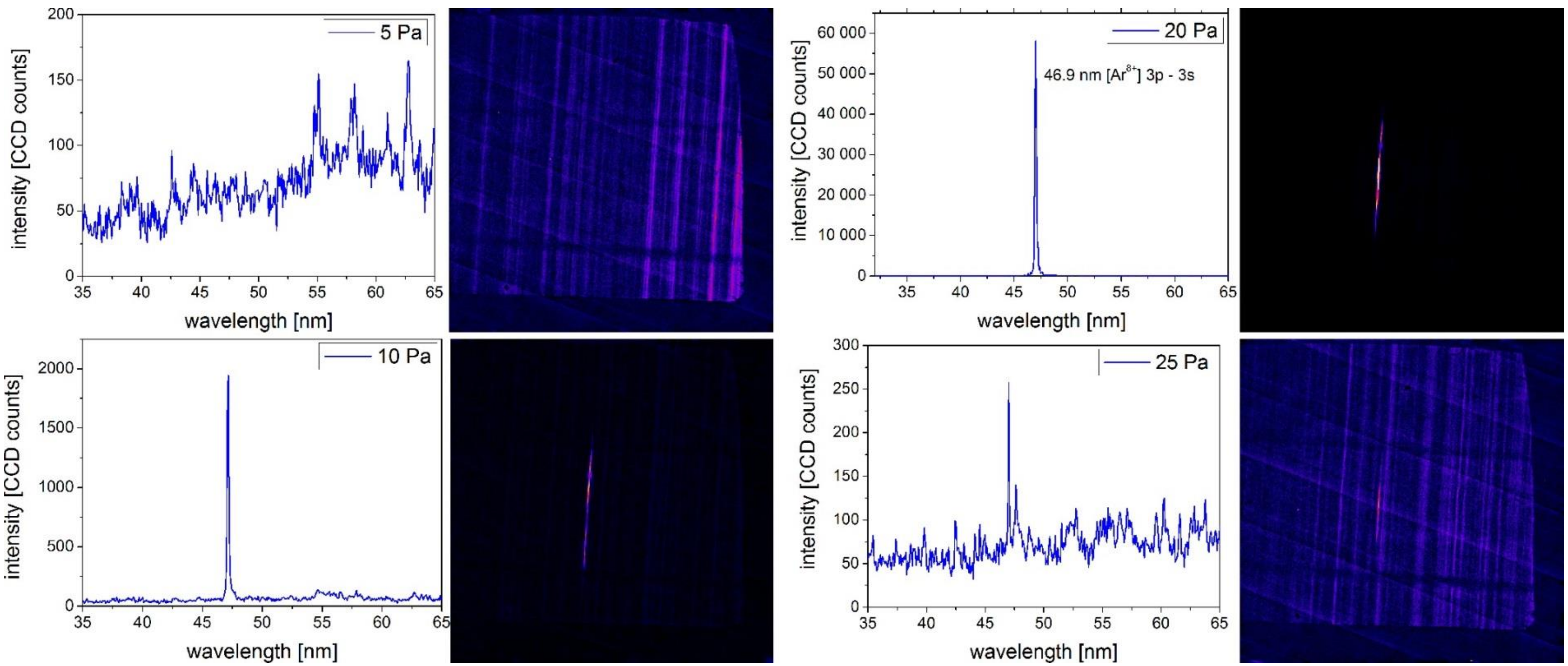
Nevrkla, M., "Capillary Discharge XUV Radiation Source," Acta Polytech. **49**(2) (2009)

Ar^{8+} LASER 46.9 nm CTU

Spectral measurements

Experimental results

- **EUV spectrometer**, reflection Au grating 300 lp/mm.
- **BI-CCD kamera** 12,3 × 12,3 mm, 512 x 512 pixels,
0,05 ÷ 5 keV, dynamic range 20.000 : 1.

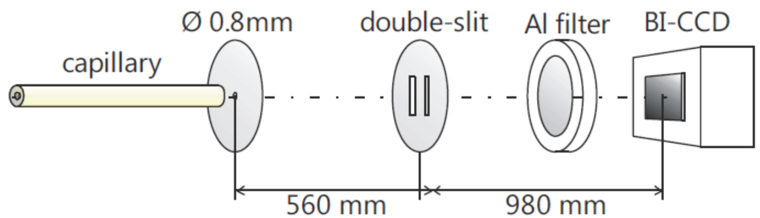


M. Nevrkla, A. Jančárek, P. Vrba, and M. Vrbová, “Capillary discharge apparatus for intense XUV radiation generation,” *IET Eur. Conf. Eur. Pulsed Power 2009. Inc. Cern Klystron Modul. Work.*, pp. 1–3, 2009.

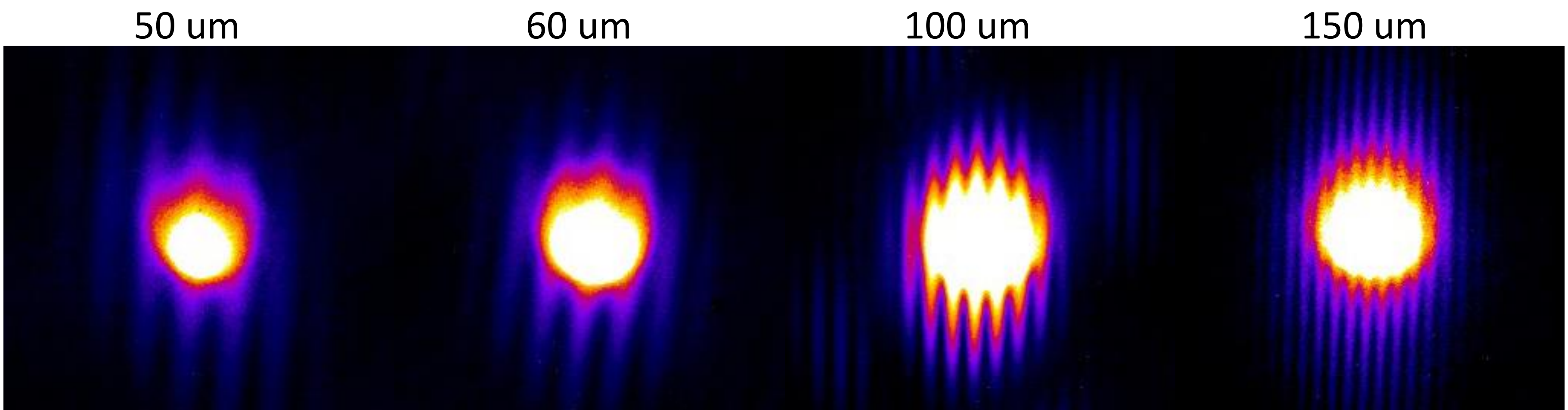
Ar^{8+} LASER 46.9 nm CTU

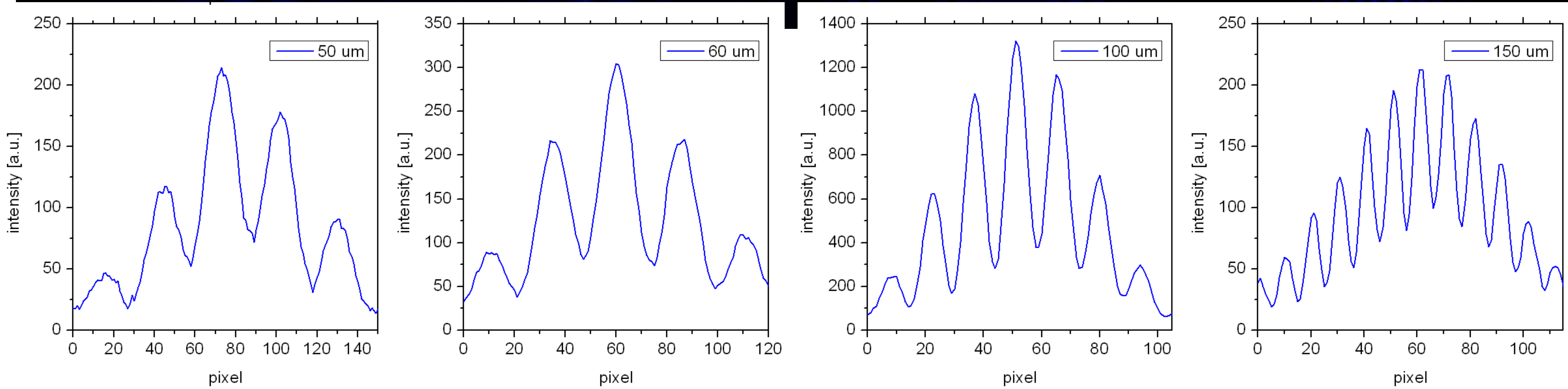
Double slit experiment

Interferograms and space coherence



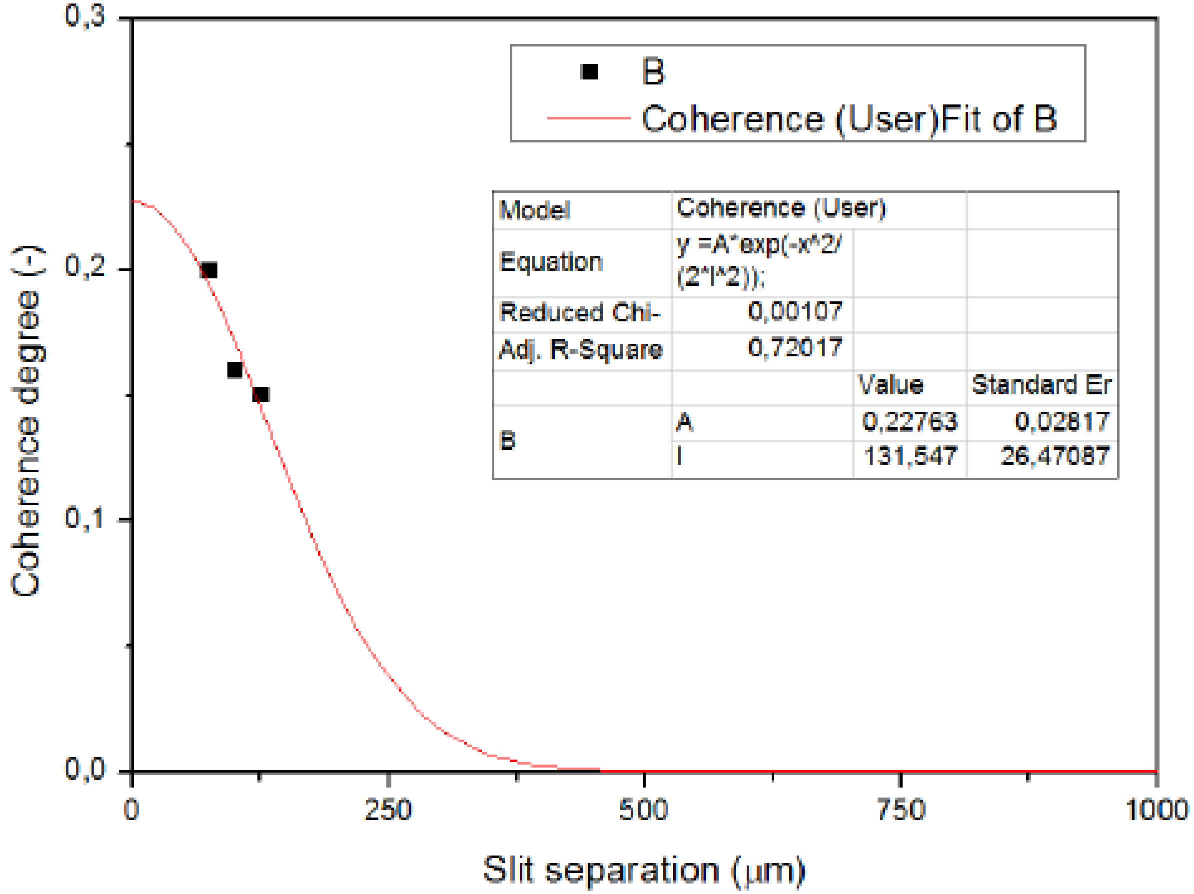
Slit separation (25 um slit width)





Ar^{8+} LASER 46.9 nm CTU

Beam profile and space coherence

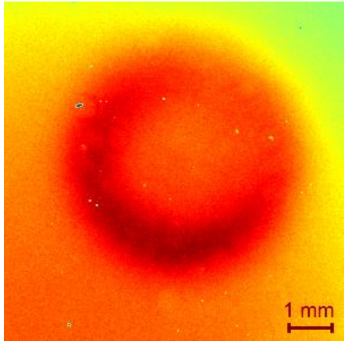


Novak J., Nevrkla M., Jancarek A. *Measurment of characteristics XUV capillary laser,* SPIE proccedings 8076, Prague, 2011

Ar^{8+} LASER 46.9 nm CTU (… multiple capillaries)

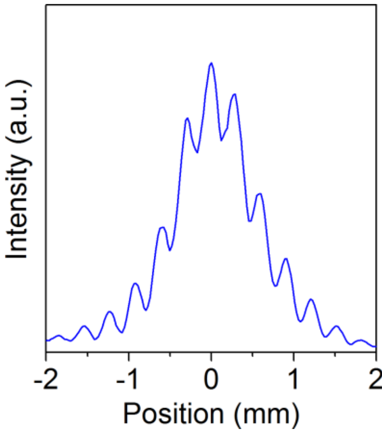
Beam profile, space coherence, spectrum and PMMA lithography

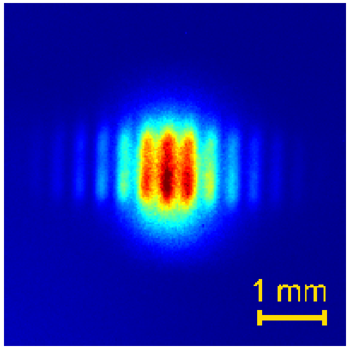
Beam profile, BI-CCD,
1.5m from capillary end,
0.8 um Al filtered



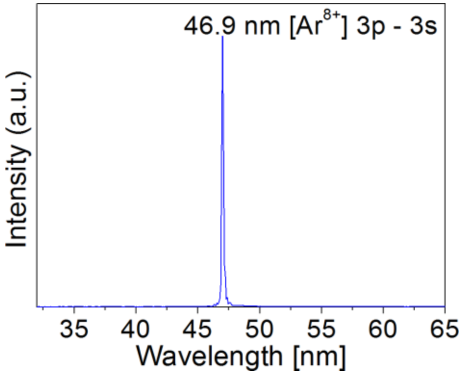
Double-slit interference pattern

- 150um slit separation, 25um slit width
- 560mm from capillary to slit
- 980 mm double slit to BI-CCD
- 0.8 um Al filtered

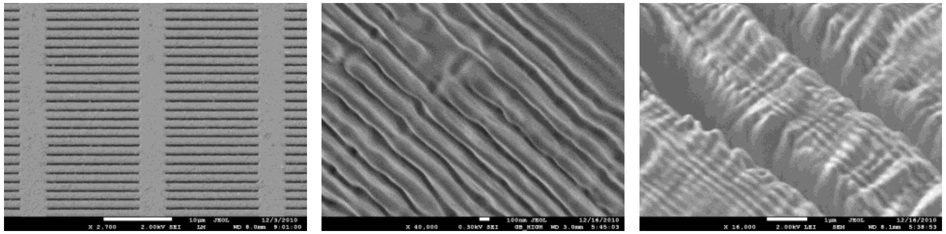




Time-integrated spectrum
0.8 umAl filtered



Contact lithography by PMMA ablation

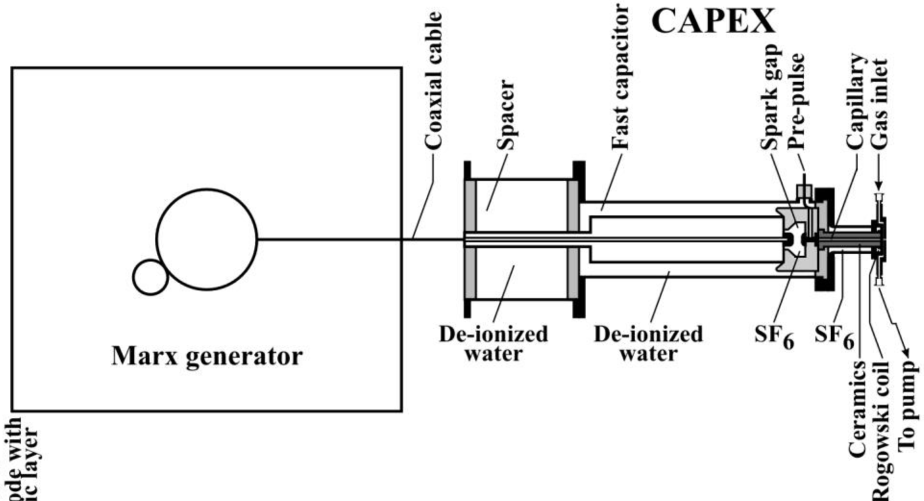


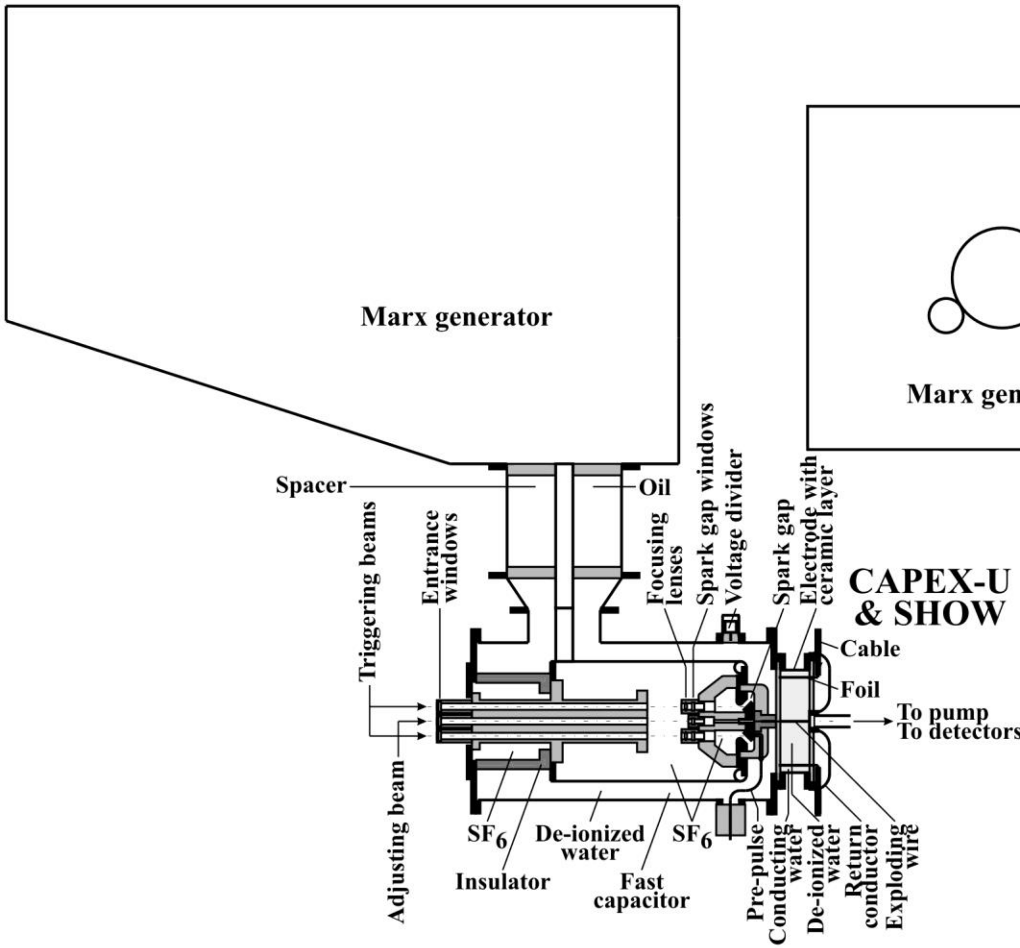
Laser beam parameters

wavelength	46.9 nm
energy/pulse	>0.1 µJ
Divergence 2θ	3 ÷ 5 mrad
Coherence angle $2\theta_c$	(0.5 ± 0.1) mrad
Coherence degree	0.22 ± 0.03

Jančárek, A et al. “Lower current pulse XUV capillary discharge source,” XXIX Int. Conf. Phenom. Ioniz. Gases, Cancún (2009).

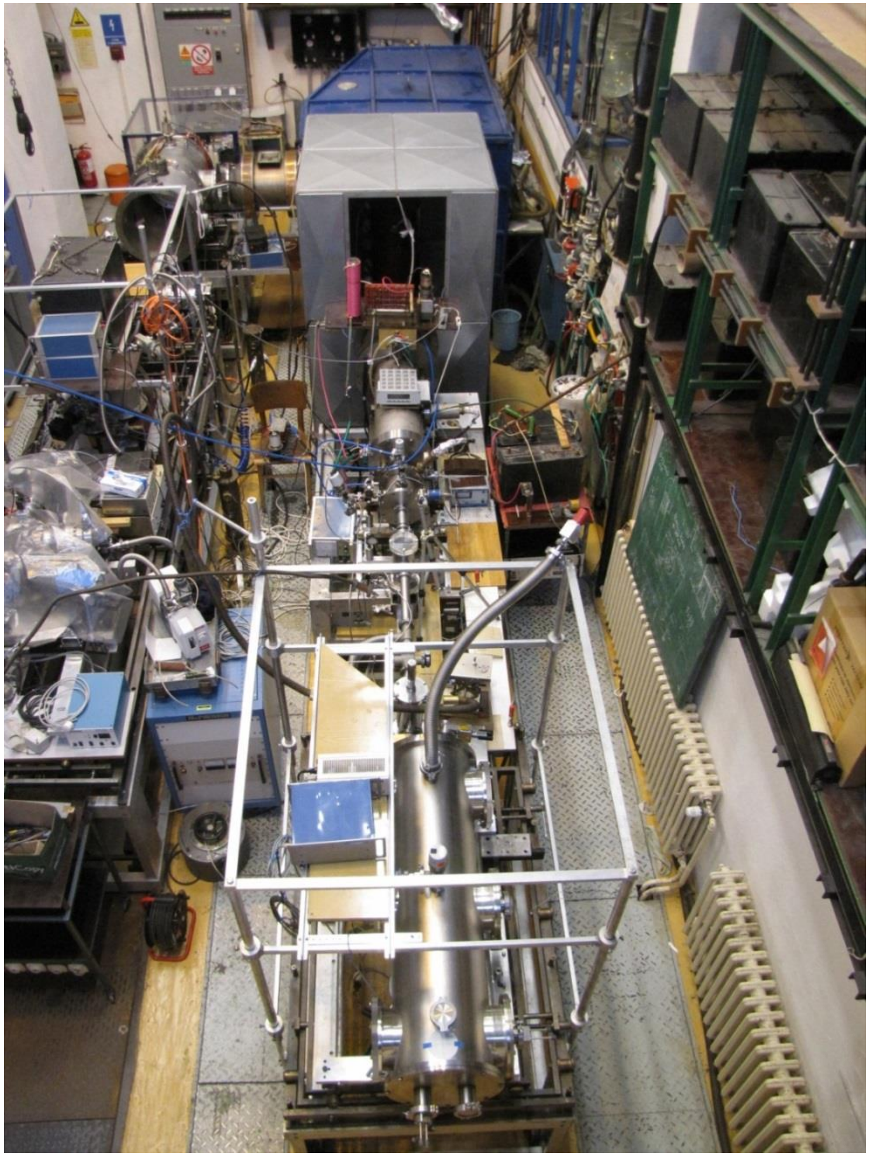
Ar^{8+} LASER 46.9 nm IPP CAS





		CAPEX	CAPEX-U	
Marx gen.	stages	10	8	
	erected C_M	12.0	12.5	nF
	erected U_M	400	600	kV
	stored E_M	0.96	2.25	kJ
spacer	filling	SF_6	oil	
fast capacitor	outer	∅262	∅550	mm
	inner	∅158	∅426	mm
	length	675	730	mm
	capacitance	6	12.7	nF
	char.imped.	3.37	1.7	Ω
main spark gap		selfbreakd.	laser	
load		capillary	wire	
	walls	ceramics	water	

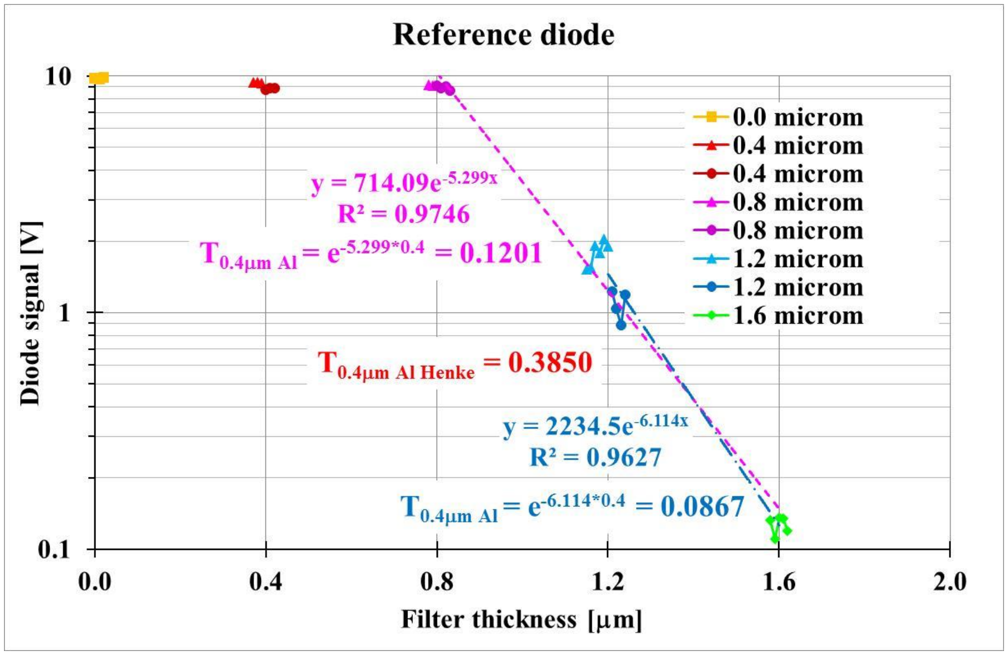
Ar^{8+} LASER 46.9 nm IPP CAS



Ar^{8+} LASER 46.9 nm IPP CAS

Energy of the laser pulse (vacuum diode with gold cathode)

Attenuation of Al filters

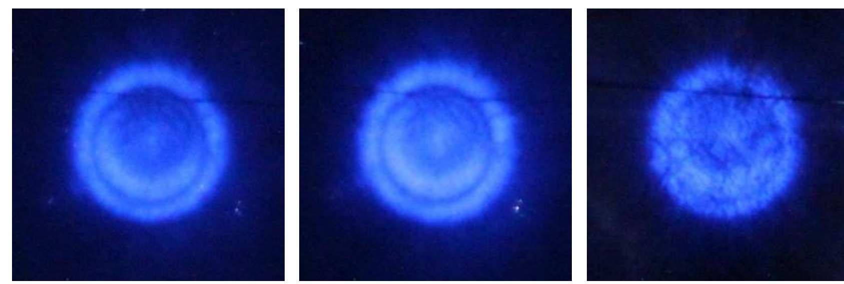


Influence of scattering on filters?

The luminescence-screen (~110 cm from the capillary output) photographed with increasing 0.4 μm Al filter-screen distance (the dimension of rectangle side is 10 mm)

the distance from the screen:

4 mm 8 mm 252 mm



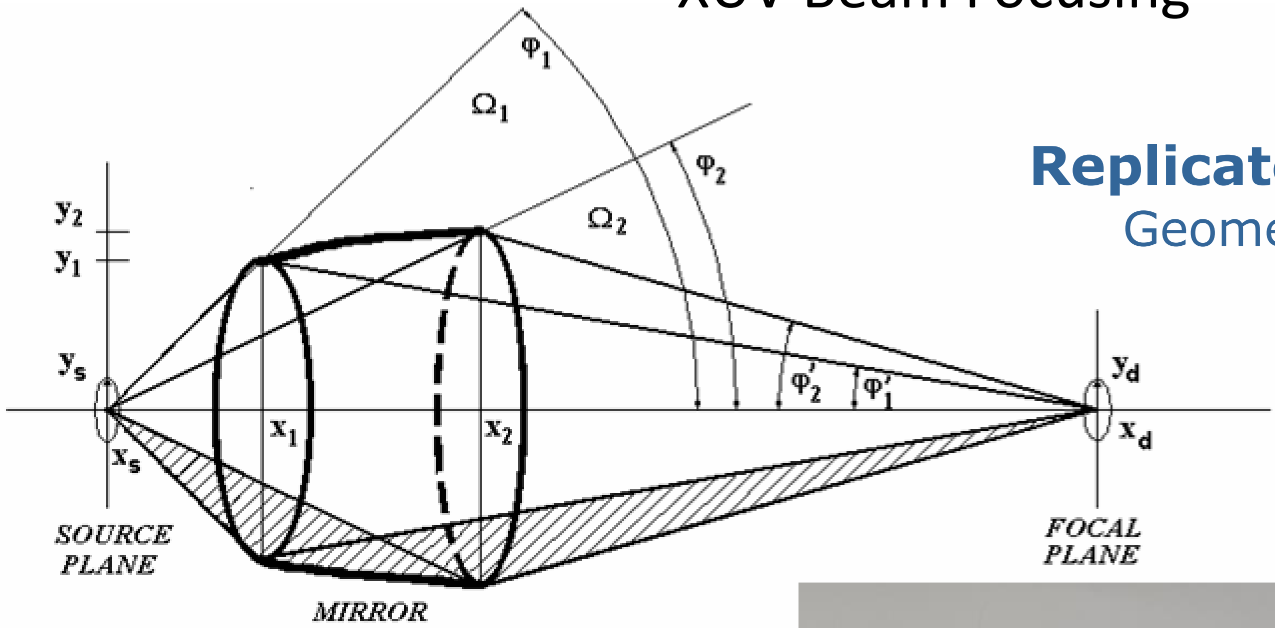
the footprint of the beam

Pulse energy after correcting attenuation of filters:

E_{400mm} = 792 μJ : transmission $T_{0.4\mu m\ Al}$=0.1201

E_{400mm} =1.52mJ : transmission $T_{0.4\mu m\ Al}$=0.0867

XUV Beam Focusing

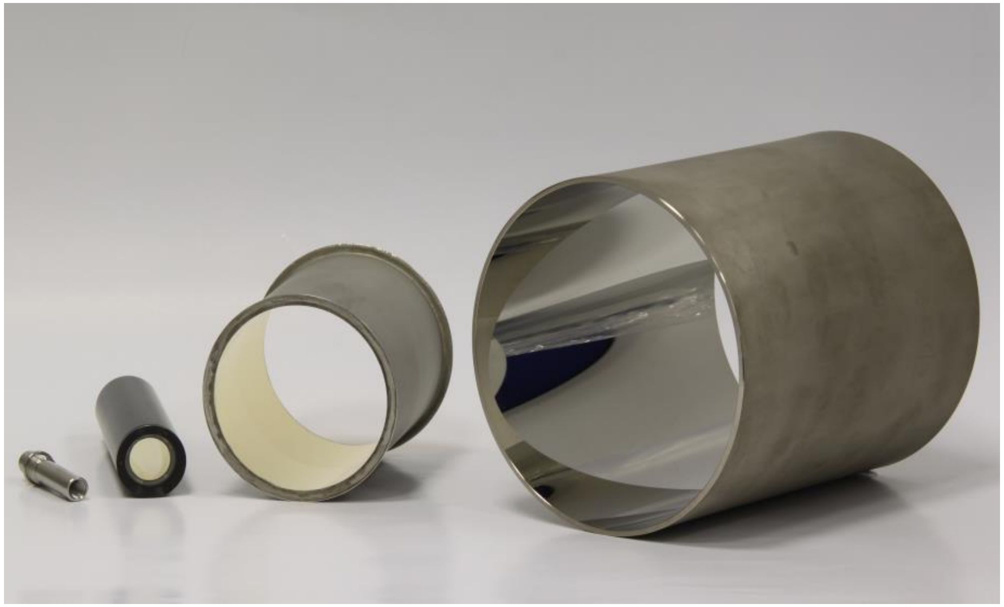


Replicated GI Mirrors

Geometry and size

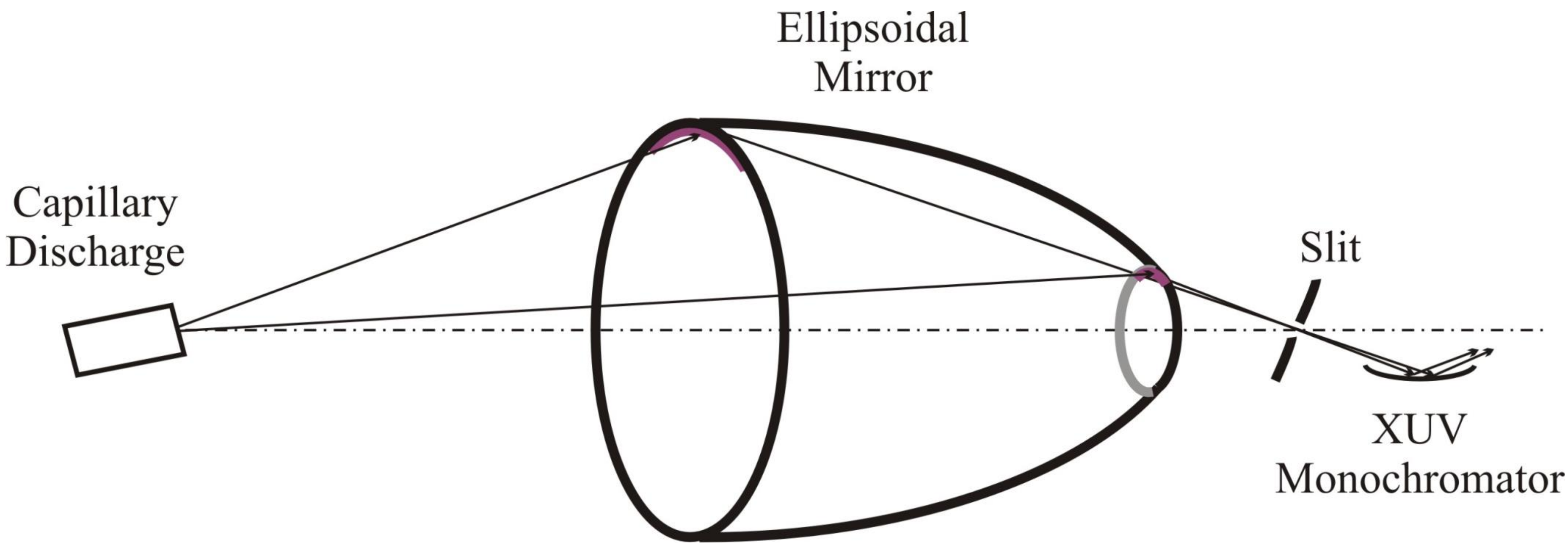
Example: Ellipsoidal mirror

- Mirror surface has shape of rotational ellipsoid
- Source is placed in left focus
- Detector or sample is placed in right focus
- Radiation strikes mirror surface at grazing angles 0,5° ÷ 20°
- Mirror is focusing radiation from left focus on right focus



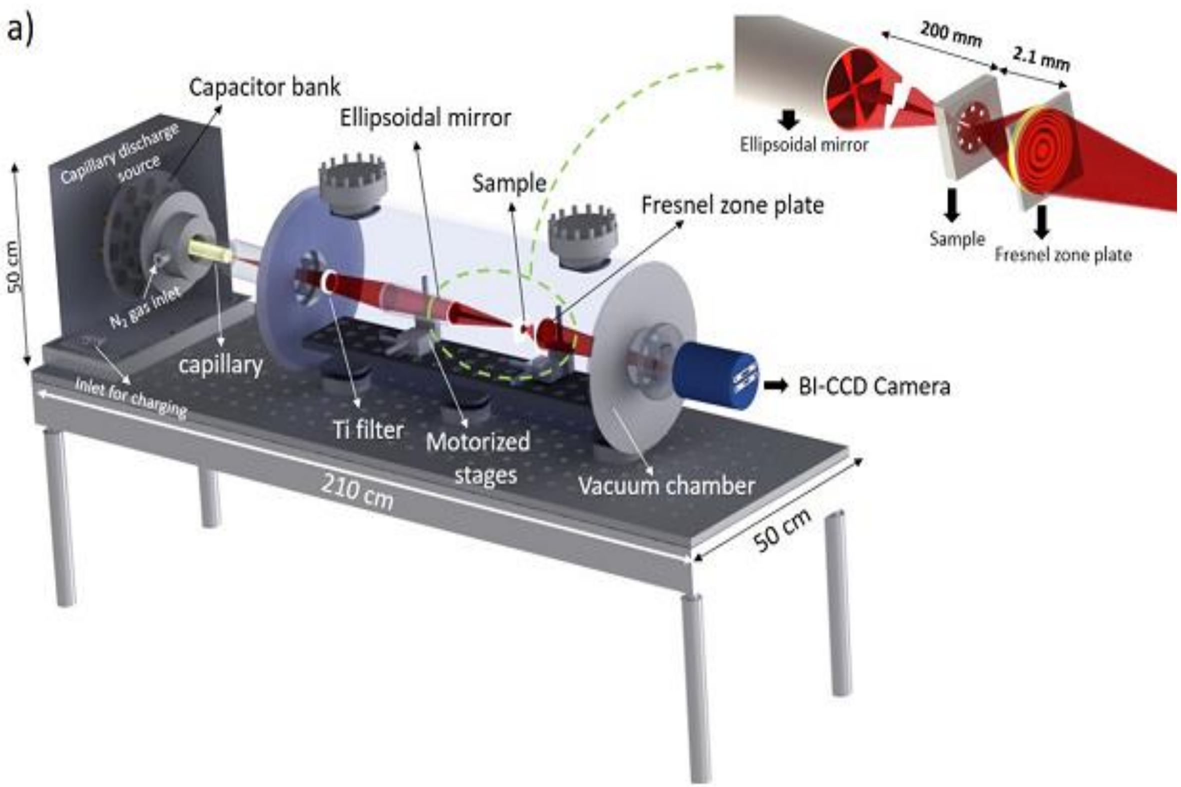
XUV Beam Focusing

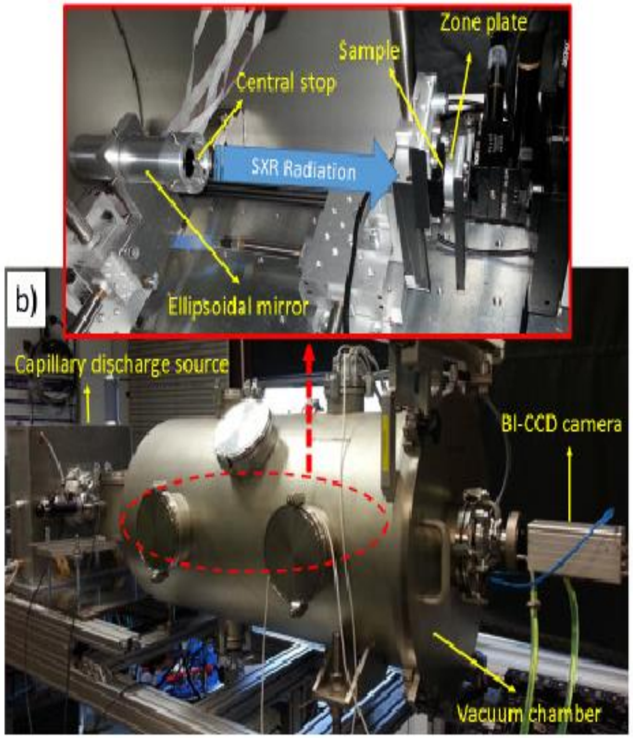
Experimental Arrangement of XUV Spectrometer with XUV Optics



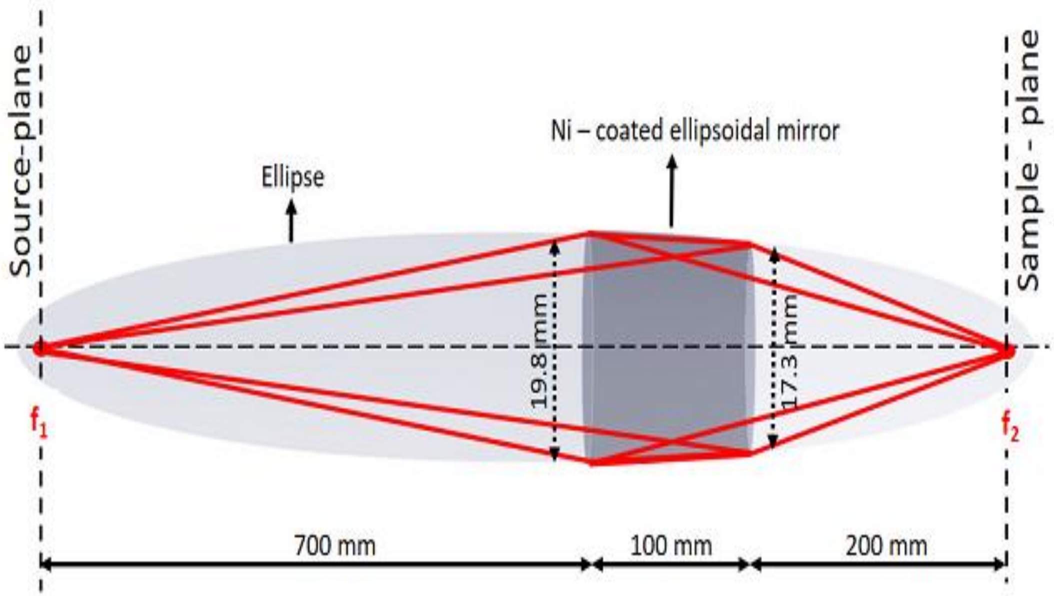
EUV microscope with capillary discharge plasma source (Nitrogen, λ = 2.88 nm), ellipsoidal grazing incidence condenser and Fresnel Zone objective

(Czech Technical University in Prague)

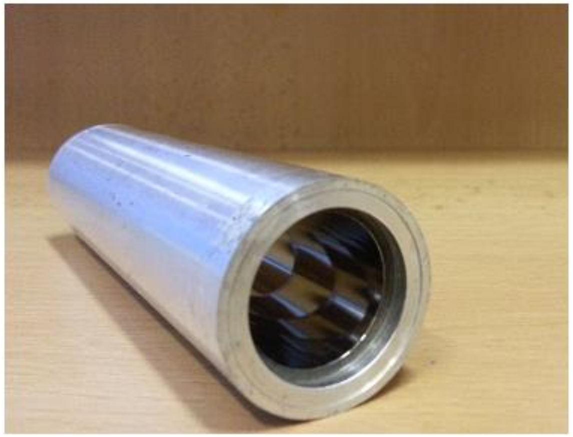




Ellipsoidal condenser for SXR microscope

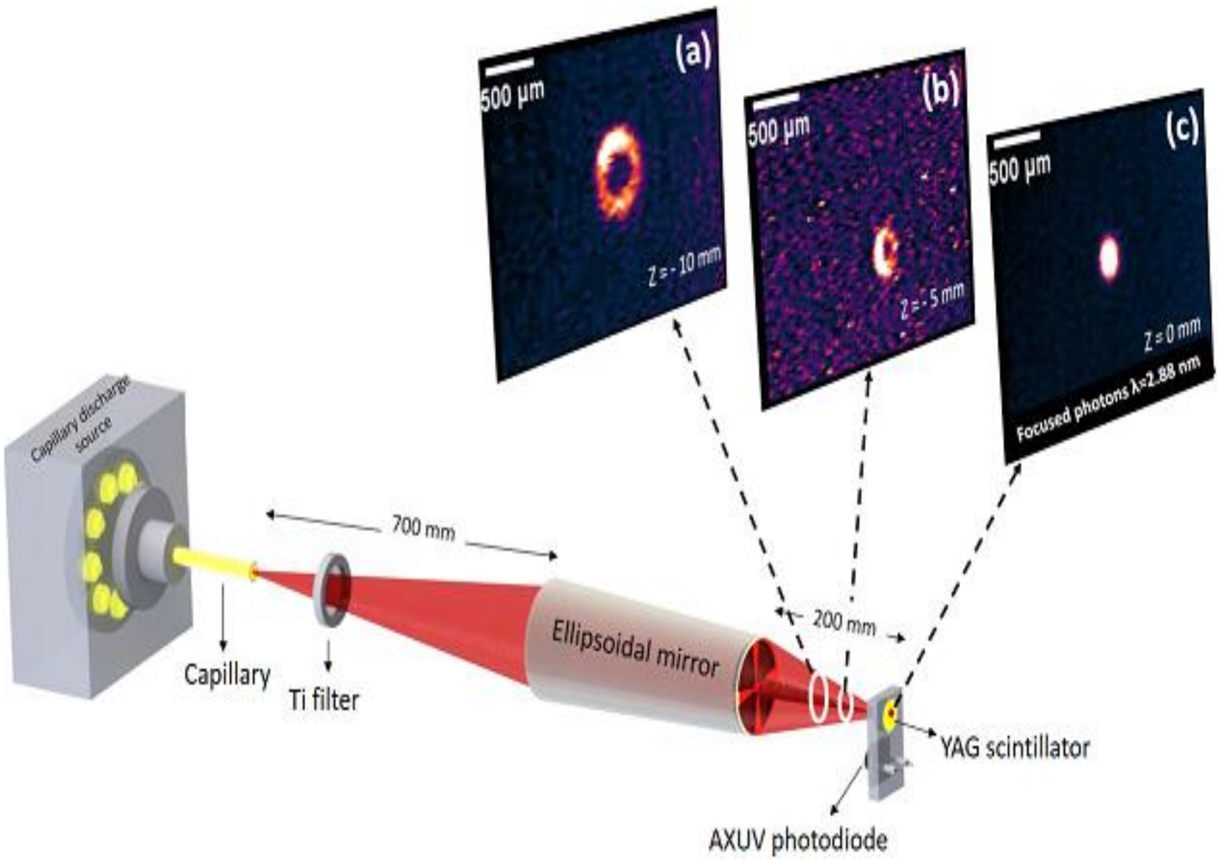


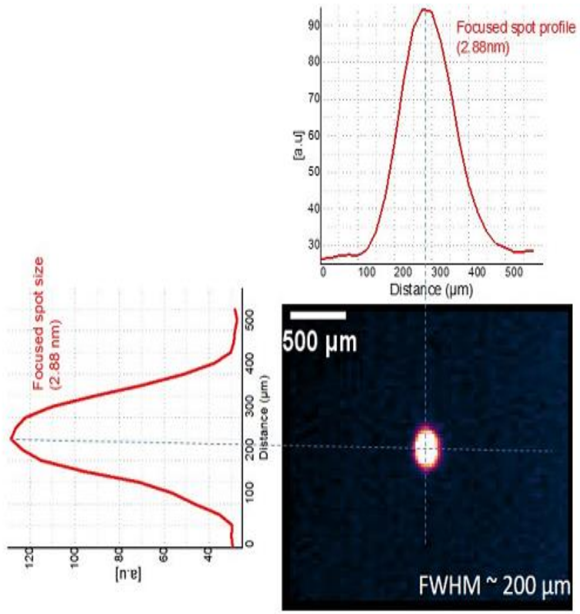
Ellipsoidal condenser mirror geometry



Ni-coated ellipsoidal condenser mirror

Measured beam images before the sample plane





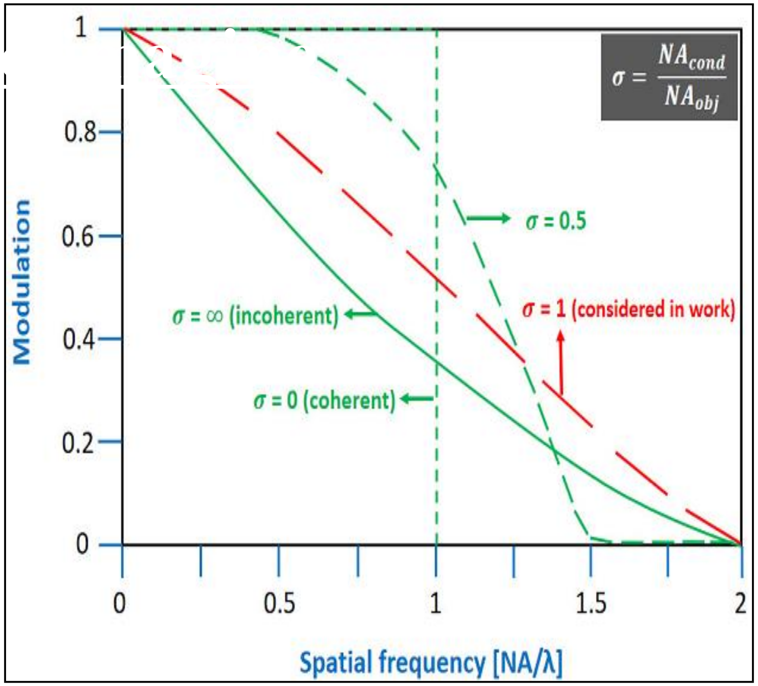
Focal spot image (λ=2.88 nm)

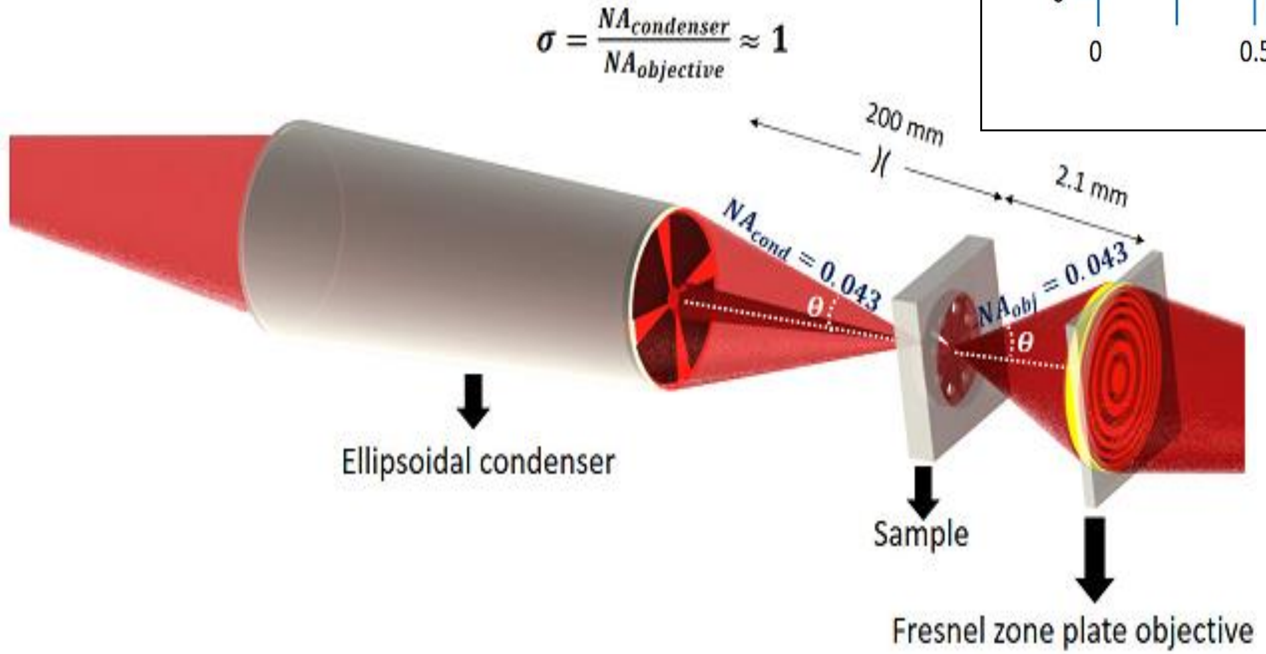
M. Fahad Nawaz, A. Jancarek, M. Nevrkla, P. Wachulak, J. Limpouch, L. Pina, " Focusing and photon flux measurements of the 2.88 nm radiation at the sample plane of the soft X-ray microscope, based on capillary discharge source", in Proc SPIE 2015,p. Art No. 951014.

Imaging scheme of the soft X-ray microscope

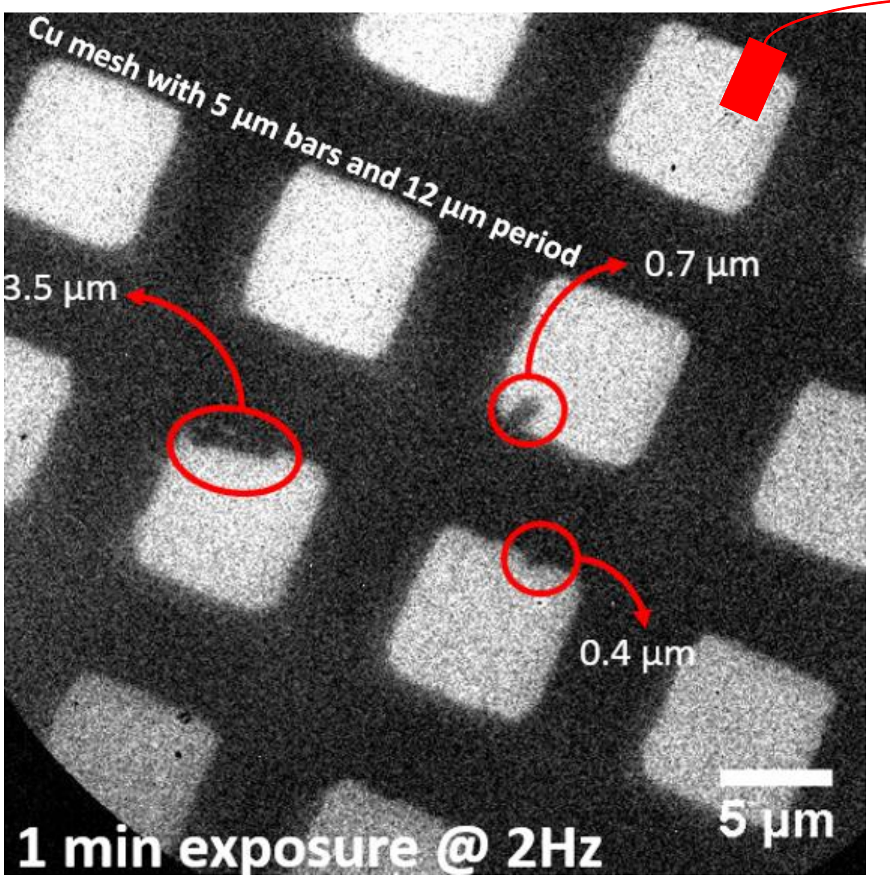
$$NA_{condenser} = NA_{FZP} = 0.043$$

Ensuring optimal illumination

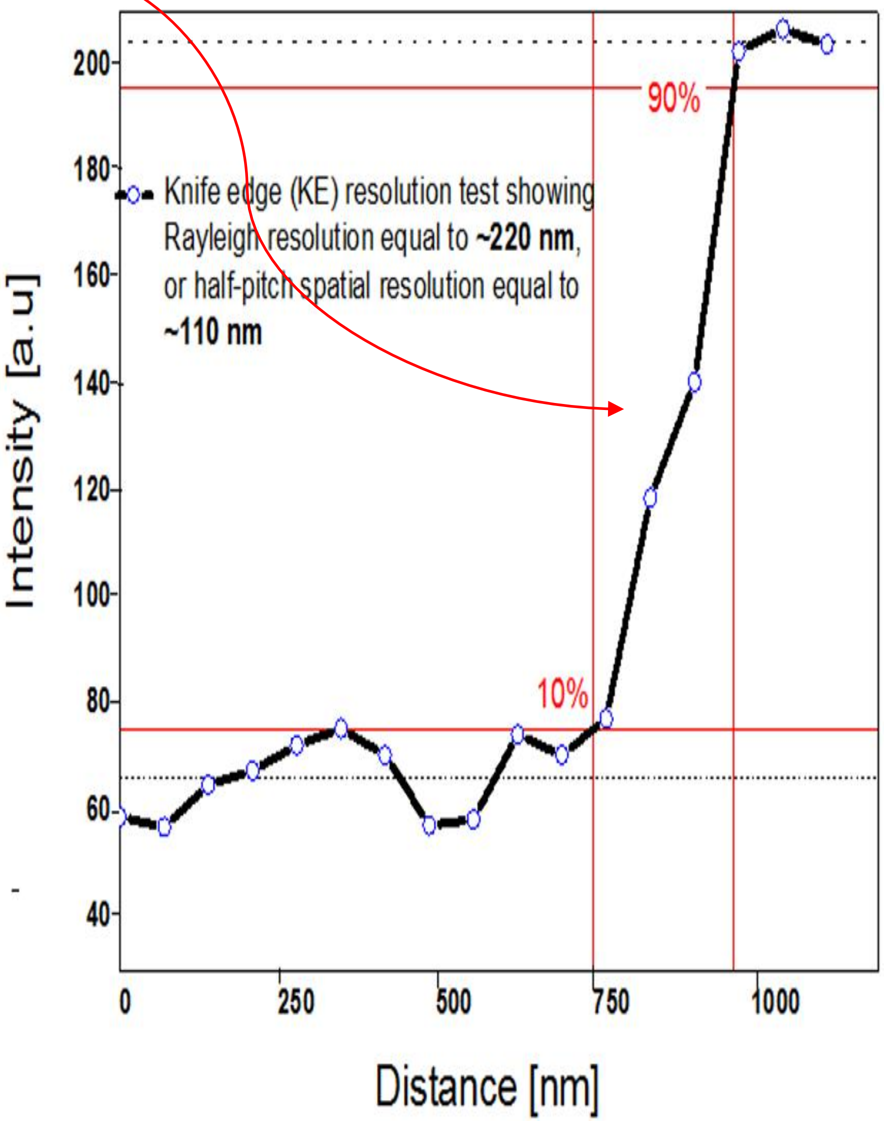




Soft X-ray microscope resolution test



Sample: Cu mesh



Summary

DPP, LPP, HHG sources comparison

- Pulsed Energy
- Repetition rate
- Lifetime
- Lasing, coherence
- Focusibility – source size, system geometry
- Optics
- Compactness
- Cost

THANK YOU FOR ATTENTION

Prague